RESEARCH REPORT

The Many-Worlds Interpretation as a Structural Bridge to Quantum Gravity

Towards the Hypothesis MWI = Cosmological Multiverse

Theoretical Framework for Doctoral Thesis in Physics

Quantum Cosmology · Quantum Gravity · Foundations of Quantum Mechanics

Executive Summary

This report explores a central and hitherto unsatisfactorily answered question in cutting-edge theoretical physics: what structural contribution — not merely interpretive — can the Many-Worlds Interpretation (MWI) make to the two leading candidates for a quantum theory of gravity, Loop Quantum Gravity (LQG) and M-Theory/String Theory?

The starting thesis is that the redundancy of universes observed in modern cosmological models — MWI, eternal inflation, cyclic models, the string landscape — is not a failure but a signal that these theories describe the same ontological substrate from different epistemological perspectives. Resolving this redundancy demands that MWI cease to be a mere interpretation and become a structural element that solves critical, irreducible problems within LQG and M-Theory.

> *Central hypothesis: MWI = Cosmological Multiverse is not a speculative equation but the recognition that the quantum universe (ontological background) and the relativistic-cosmological multiverse (epistemological levels) are the same structure described in two languages. A complete quantum theory of gravity must make this equivalence exact and derivable.*

The report identifies two specific and asymmetric structural contributions: in LQG, MWI resolves the problem of time and allows the arrow of time to be derived without appealing to external conditions; in M-Theory, MWI offers an ontological selection principle for the string landscape and provides the basis for understanding the bulk as emergent from the quantum entanglement of branches of the universal wave function.

1. The Redundancy Problem in Modern Physics

1.1 Anatomy of the Problem

Contemporary theoretical physics faces an unprecedented proliferation of multiverses. Each cutting-edge theory seems to generate, as an almost inevitable by-product, a multiplicity of universes. This phenomenon is not accidental: it is the manifestation of a deep structural tension between the quantum formalism and classical-relativistic cosmological models.

The main generators of multiverses are the following:

- MWI (Tegmark Level III): every quantum event branches the universe into multiple branches. The number of branches grows exponentially with each interaction. In the cosmological limit, the wave function of the universe simultaneously contains all possible histories.
- Eternal Inflation (Level II): the inflaton field generates regions of false vacuum that never stop inflating, nucleating bubble universes with different physical constants and broken symmetry groups. The number of bubble universes is potentially infinite.
- Cyclic Models (ekpyrotic, LQC with Big Bounce): the universe collapses and bounces indefinitely. Each cycle constitutes in principle a separate universe with different initial conditions. Quantum genesis of universes ex nihilo.
- String Landscape (approximate Level IV): M-Theory admits an estimated 10^500 distinct stable vacua, each corresponding to a universe with different low-energy physics.

The problem is not the existence of multiple universes per se, but the redundancy: MWI produces the same universe as Tegmark's Level I (causally disconnected regions), the same as Level II (universes with different constants), and both produce the same multiverse as the string landscape. These are four descriptions of the same thing formulated in mutually incompatible languages.

> *Formal problem: if MWI and eternal inflation generate the same set of universes (all those consistent with the laws of physics), then the final theory must derive one from the other or show they are dual. The absence of this bridge is the central epistemological crisis of current quantum cosmology.*

1.2 Why the Redundancy Requires a Quantum-Gravitational Solution

The redundancy cannot be resolved within any of the theories separately. It requires precisely a quantum theory of gravity operating at the Planck scale, unifying the quantum formalism with the geometry of spacetime. The reasons are as follows:

- MWI operates over Hilbert space without reference to the geometry of spacetime. It cannot discriminate between branches corresponding to different geometries.
- LQG quantises geometry but lacks a standard quantum interpretation: the preferred basis problem is equivalent to the preferred basis problem of MWI.
- M-Theory has the landscape but no selection principle. The anthropic principle is an epistemic answer, not an ontological one.
- Holography (the holographic principle, AdS/CFT) suggests that bulk spacetime emerges from quantum information on the boundary, implying that MWI branches and bulk geometries are related by duality, not by contingency.

2. MWI and Loop Quantum Gravity: The Problem of Time and the Temporal Arrow

2.1 The Problem of Time in LQG: Technical Description

The problem of time is universally recognised as the deepest obstacle in LQG and in quantum cosmology generally. Its nature is simultaneously technical and philosophical, and no other interpretation of quantum mechanics has offered a structural solution to it.

In the canonical formalism of LQG, the central equation is the Wheeler-DeWitt (WdW) equation in its discrete version:

$$\hat{H}\,|\Psi\rangle = 0$$

This equation imposes that the total Hamiltonian operator applied to the wave function of the universe gives zero. There is no explicit time parameter. The universe, described in its totality, is a static object in superspace. There is no temporal evolution in the conventional sense.

The consequences are devastating for observable physics:

- There is no way to define 'before' and 'after' at a fundamental level. Causality is an emergent property that LQG cannot derive from its basic equations.
- The arrow of time — the fact that entropy grows in one direction — has no correlate in the Wheeler-DeWitt equation. Thermodynamic time is external to the formalism.
- Classical General Relativity must emerge as a semiclassical limit, but the mechanism by which a timeless equation generates a dynamic geometry with a well-defined time is obscure.
- Attempts to introduce an 'internal reference time' (relational or York time) are ad hoc and do not resolve the problem in the deep quantum regime.

2.2 Why MWI is the Only Interpretation That Can Resolve the Problem of Time

This is the central thesis of this section and the sharpest structural contribution MWI can make to LQG. Let us analyse why other interpretations fail and why MWI does not.

Interpretation	Treatment of time	Compatible with $\hat{H}\|\Psi\rangle=0$	Residual problem
Copenhagen	External classical time required	No — requires an exterior observer	Self-reference: there is no exterior to the universe
Bohm (hidden variables)	Absolute Newtonian background time	No — requires a privileged foliation	Violates Lorentz invariance; superdeterminism
Consistent histories	Time defined by sets of histories	Partially	Not derivable without Born rule; arbitrariness
MWI (Everett)	Time emerges through	Yes — the wave	Requires deriving the

Interpretation	Treatment of time	Compatible with $\hat{H}\|\Psi\rangle=0$	Residual problem
	decoherence between branches	function is timeless and branching	Born rule ontologically

MWI is the only interpretation that begins from a timeless wave function and derives time as an emergent property of entanglement between subsystems. This is exactly what the Wheeler-DeWitt equation requires. The mechanism is as follows:

2.2.1 The Page-Wootters Time as a Natural Consequence of MWI

In 1983, Don Page and William Wootters proposed a mechanism (PW) in which time emerges from the entanglement between a quantum 'clock' and the rest of the universe. The global state satisfies $\hat{H}|\Psi\rangle = 0$, but internal observers perceive temporal evolution because they are entangled with the clock.

This PW mechanism is, in essence, a corollary of MWI applied to closed quantum systems: each branch of the wave function of the universe contains a complete history from the perspective of internal observers, who perceive a coherent flow of time because decoherence selects classically consistent branches. The appearance of temporal evolution is the result of correlations between subsystems within each branch.

> *MWI's contribution to LQG: the Wheeler-DeWitt equation does not require an external time because MWI provides time internally. The branches of the universal wave function, differentiated by decoherence in the spin network (spin foam), generate the semiclassical time parameter that LQG needs to recover General Relativity as a low-energy limit. Without MWI, LQG requires an external reference time that its own formalism cannot supply.*

2.2.2 The Arrow of Time: Asymmetry Emerging from Branching

The arrow of time is one of nature's great asymmetries: the laws of physics are symmetric under time reversal (CPT), yet experience and thermodynamics exhibit an irreversible temporal direction. LQG cannot derive this asymmetry from its timeless formalism.

MWI offers an elegant and structural solution to the problem. The argument has the following structure:

- The wave function of the universe evolves unitarily and reversibly (Schrödinger). There is no intrinsic temporal asymmetry.
- Decoherence with the environment produces an effectively irreversible branching: branches separate but do not recombine on macroscopic scales due to the enormous number of environmental degrees of freedom.
- The irreversibility of branching — the practical inability to reverse complete decoherence — is the source of the arrow of time. Entropy grows because the number of branches accessible to an internal observer grows monotonically.
- In the context of LQG, the spin network in the past is 'simpler' (fewer nodes and links) than in the future, and the branching of the wave function over the spin network encodes this asymmetry naturally.

This argument cannot be reproduced within the Copenhagen interpretation (which requires a pre-existing external classical time) or Bohmian mechanics (which postulates an absolute Newtonian time, making the arrow of time an assumption rather than a derived result).

2.3 Deriving General Relativity from LQG + MWI

One of the most serious and least discussed problems of LQG is the difficulty of recovering classical General Relativity in the low-curvature limit. Einstein's equations must emerge as a semiclassical approximation of the spin network, but the mechanism is technically very complex and conceptually obscure.

MWI's contribution at this point is indirect but essential: decoherence between branches of the wave function defines which classical geometries are stable and persistent. The geometries that satisfy Einstein's equations are precisely those that survive decoherence because they are the ones that correlate consistently with matter states. Quantum geometries that do not satisfy Einstein's equations are destroyed by interference between branches.

> *In other words: General Relativity is not an input of LQG but an output of the decoherence process that defines the classically stable branches of the wave function of the spin network. MWI is the mechanism by which LQG recovers classical physics.*

This argument can be formalised through the programme of 'emergent geometrodynamics': the classical geometry of spacetime is the average geometry over those branches of the wave function of the spin network that are mutually coherent. Decoherence eliminates superpositions of geometries and selects the observed classical geometry.

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3. MWI and M-Theory: The Landscape as Branch Structure and the Emergent Bulk

3.1 The Landscape Problem in M-Theory

M-Theory/String Theory faces a radically different problem from LQG but equally devastating: the overabundance of solutions. The vacuum of M-Theory is not unique. Compactifications of the extra dimensions admit an astronomically large number of stable configurations (estimated at 10^500 or more), each corresponding to a universe with different low-energy physics. This proliferation is known as the string landscape.

The problem has two aspects:

- Selection problem: why does our universe have the physical constants it has? The anthropic principle is the standard answer, but it is epistemic (we observe this universe because we are observers compatible with it) rather than ontological (it does not explain why this vacuum exists at all).
- Prediction problem: if all vacua exist, M-Theory cannot make predictions about the physical constants of our universe without a probability distribution over the landscape. The landscape measure is an open problem with no consensus solution.

3.2 MWI as an Ontological Selection Principle for the Landscape

MWI's contribution to the landscape problem is conceptually profound. The central idea is as follows: the vacua of the string landscape are not separate universes in a metaphysical sense but branches of the universal wave function of the universe.

If the wave function of the universe evolves unitarily from an initial state — consistent with the Hartle-Hawking no-boundary proposal or a quantum initial singularity — then all vacua of the landscape accessible from that initial state appear as branches of the wave function, weighted by their squared amplitudes (Born rule).

> *This radically transforms the problem: the anthropic principle becomes unnecessary. Each landscape vacuum has a probability amplitude defined by the initial wave function of the universe. The question 'why this vacuum?' becomes 'what is the amplitude of this branch?', which is a technical question within the MWI formalism, not an appeal to observers.*

This equivalence — landscape vacua = branches of the wave function — is the mathematical formulation of the MWI = Multiverse hypothesis in the context of M-Theory. The implications are:

- The landscape measure is the Born measure over Hilbert space. It is not an additional measure imposed on the landscape; it is the standard quantum measure.
- The distribution of physical constants across universes of the landscape is in principle predictable: it is determined by the amplitudes of the initial wave function of the universe, which depend on the dynamics of M-Theory at the Planck scale.
- The anthropic principle becomes a selection tool within a single quantum formalism, not an independent and philosophically questionable principle.

3.3 The Bulk as Emergent from Quantum Entanglement: ER = EPR and MWI

This is perhaps the most speculative but also the most fascinating contribution that MWI can make to M-Theory. It rests on the ER = EPR conjecture (Einstein-Rosen = Einstein-Podolsky-Rosen), proposed by Juan Maldacena and Leonard Susskind in 2013.

The ER = EPR conjecture states that entangled particle pairs (EPR) are connected by quantum Einstein-Rosen wormholes (ER). Quantum entanglement and geometric connectivity are the same structure described in two languages. This has extraordinary consequences for the relation between MWI and bulk geometry:

3.3.1 MWI Branches as Distinct Bulk Geometries

In the holographic formalism of AdS/CFT, the gravitational bulk emerges from the quantum field theory on the boundary. If the boundary theory is in a superposition of states (as naturally occurs in MWI), then the corresponding bulk is a superposition of geometries.

Decoherence between branches of the wave function on the CFT boundary corresponds to the selection of a classical bulk geometry. Each coherent branch of the boundary wave function generates a different bulk geometry. The decoherence process in MWI is the process of 'crystallisation' of the bulk from the quantum fog of possible geometries.

> *Precise formulation: the AdS bulk is not a fundamental object but an emergent representation of quantum entanglement on the CFT boundary. MWI branches in the boundary theory correspond to distinct entanglement states, and therefore to distinct bulk geometries. The*

> *equation MWI = Multiverse, in the context of AdS/CFT, reads: 'distinct branches of the boundary wave function generate distinct cosmological universes (bulks)'.*

3.3.2 The 'It from Qubit' Initiative and Its Connection with MWI

The 'It from Qubit' programme, driven by researchers including Mark Van Raamsdonk, Netta Engelhardt and Ahmed Almheiri, systematically explores how spacetime emerges from quantum entanglement. Its most relevant results in relation to MWI are:

- Bulk geometry is encoded in the entanglement structure of the boundary. Destroying entanglement between two boundary regions disconnects the corresponding bulk regions (spacetime 'tears').
- Maximally entangled boundary states correspond to Einstein-Rosen wormhole seeds in the bulk (ER = EPR).
- The black hole information paradox is resolved because information is not lost in the bulk but is encoded in the quantum correlations of the boundary, which correspond to branches of MWI.
- The Born rule emerges naturally in this formalism: the probabilities of different bulk histories are the squared amplitudes of boundary states.

MWI is the conceptual glue that unites all these pieces: the superposition of states on the CFT boundary (MWI) generates the superposition of bulk geometries, decoherence selects the classical branches (stable geometries), and the Born rule provides the probability measure over cosmological histories.

3.4 What MWI Contributes That No Other Interpretation Can Offer to M-Theory

The foregoing argument can be made more precise through a direct comparison. The alternatives to MWI fail in the context of M-Theory for the following reasons:

Interpretation	Treatment of the landscape	Compatibility with holography	Problem in M-Theory
Copenhagen	Chooses a vacuum by collapse (who collapses the universe?)	Incompatible: no exterior observer	The universe has no external classical observer
Bohm	A single realised vacuum with hidden trajectories	Only superficially compatible	Cannot explain transitions between vacua; implies superdeterminism at cosmological scale
Consistent histories	Multiple histories without clear ontology	Partially compatible	Does not assign reality to unrealised vacua; arbitrary measure
MWI	All accessible vacua are real branches weighted by Born	Fully compatible: branches = CFT boundary states	Requires deriving the Born rule, but holography can provide it

The case of Bohm deserves special attention. Bohmian mechanics requires a single realised world with defined particle trajectories. In the cosmological context, this implies that the extra

dimensions of M-Theory must be in a definite state, not in superposition. But the wave function of the early universe is inevitably a superposition of different compactifications. For Bohm to be consistent with M-Theory, it needs to postulate superdeterministic initial conditions that select a unique compactification from the outset — a highly restrictive and theory-unmotivated assumption.

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4. The MWI = Multiverse Hypothesis: Precise Formulation and Consistency Conditions

4.1 Two Versions of the Hypothesis

The MWI = Multiverse hypothesis can be formulated in two versions with different degrees of precision and commitment.

4.1.1 Weak Version (Epistemic Duality)

In its weak version, the hypothesis states that MWI branches and the universes of the cosmological multiverse (eternal inflation, cyclic LQC) are equivalent descriptions of the same set of possible histories of the universe, related by a change of perspective: the quantum perspective (universal wave function) vs. the classical-relativistic perspective (background spacetime).

This version is less ontologically committed but has empirical consequences: if correct, then the cosmological predictions of the inflationary multiverse must be reproducible from the MWI formalism with the same initial wave function. The distributions of physical constants across 'bubble universes' must coincide with the Born probabilities of the corresponding branches.

4.1.2 Strong Version (Ontological Identity)

In its strong version, the hypothesis states that the universes of the cosmological multiverse are identical to the branches of the universal wave function. There are not two sets of universes (the quantum ones of MWI and the cosmological ones of inflation); there is a single set of quantum-geometric structures that appear as bubble universes from a classical perspective and as branches from a quantum perspective.

> *The strong version implies that the universal wave function (ontological level 4 of the classification proposed in the thesis) contains all the information of the cosmological multiverse, and that Tegmark's epistemological levels 1, 2 and 3 are semiclassical approximations to different aspects of this wave function.*

4.2 Consistency Conditions for the Hypothesis

For the hypothesis to be scientifically rigorous, the following conditions must be satisfied:

- Condition 1 — Measure equivalence: The Born measure over MWI branches must be demonstrably equivalent to the probability measure over bubble universes of eternal inflation (landscape measure). This requires an explicit mapping between the Hilbert space of quantum cosmology and the configuration space of inflation.
- Condition 2 — Derivation of the Born rule from holography: The Born rule cannot be postulated in the ontological version; it must be derived from the fundamental quantum

level (Level 4) via the holographic formalism. Initiatives such as 'It from Qubit' provide the scaffolding for this derivation.

- Condition 3 — Semiclassical limit: The equations of General Relativity must be derivable as a semiclassical limit of the universal wave function through the MWI decoherence mechanism in LQG spin networks or M-Theory strings.
- Condition 4 — Singularities as quantum boundary conditions: Big Bang and Big Crunch singularities (in cyclic models) must appear as boundary conditions of the quantum wave function, not as physical breakdown points. LQG with MWI replaces singularities with high-density quantum states from which time emerges coherently.
- Condition 5 — Interpretation-change invariance: Observable physics (CMB fluctuation spectrum, coupling constants, large-scale geometry) must be independent of whether the MWI perspective or the cosmological multiverse perspective is used. Only then are the two perspectives genuinely equivalent.

4.3 The Role of Closed Timelike Curves (CTCs)

The universal wave function with a Closed Timelike Curve (CTC), mentioned in the thesis as a component of the model, plays a specific role in the MWI = Multiverse hypothesis. A CTC in the wave function of the universe implies that the quantum state of the universe is self-predetermining: the boundary conditions of the past and future are mutually consistent and holistically self-determined.

In the context of MWI, a quantum CTC does not generate paradoxes because the wave function branches: instead of a single state that must be consistent with itself (which would generate grandfather-type paradoxes), there exist multiple branches each internally consistent. 'Circular causality' becomes 'self-consistency of the global wave function', which is exactly what the Hartle-Hawking no-boundary proposal imposes.

> *Quantum CTC + MWI generates a finite, edgeless, and apparently static block universe from an external point of view, but one that contains an emergent arrow of time in each branch from an internal point of view. This structure reconciles the relativistic block universe with irreversible quantum dynamics.*

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5. Synthesis: Conceptual Map of the Model

5.1 Hierarchical Structure of the Proposed Model

The model that emerges from the integration of MWI, LQG, M-Theory and holography has the following hierarchical structure:

Level	Description	Nature	Associated theory	MWI's contribution
0 (Planck)	Discrete spacetime; spin network or strings	Primary ontological	LQG / M-Theory	Defines the Hilbert space over which the universal wave function acts
1	Universal wave function;	Secondary	Quantum	MWI = branch

Level	Description	Nature	Associated theory	MWI's contribution
(Quantum)	superposition of geometries and fields	ontological	cosmology; WdW equation	structure of the wave function; time emerges by decoherence
2 (Semiclassical)	Classical background geometries; General Relativity emerges	Primary epistemological	General Relativity; LQC	Decoherence selects classically stable branches; origin of GR
3 (Cosmological)	Bubble universes; string landscape; cyclic models	Secondary epistemological	Eternal inflation; ekpyrotic models	The 'universes' are branches of the wave function seen from a classical perspective
4 (Observable)	Observable universe; physical constants; CMB	Tertiary epistemological	Standard physics; observational cosmology	The probability of observing these constants is the Born amplitude of the branch

5.2 The Determining Role of Holography as a Connector

Holography (the holographic principle, AdS/CFT, 'It from Qubit') functions as the formal connector between levels 0–1 (ontological) and levels 2–4 (epistemological). Its function is twofold:

- Bottom-up: it encodes the quantum information of level 0 (spin network, strings) on a lower-dimensional boundary. MWI branches on the boundary correspond to different bulk geometries. The observable universe (level 4) is the 'holographic image' of the fundamental quantum state.
- Top-down: it allows probabilities (Born rule) and the arrow of time (asymmetry of entanglement) to be derived from the quantum level, without postulating them. The Born rule emerges from the entanglement structure of the CFT boundary.

This dual function of holography is what transforms the MWI = Multiverse hypothesis from an interpretive statement into a technical one: if holography is correct, MWI and the cosmological multiverse are dual in the technical sense of AdS/CFT.

5.3 What MWI Contributes That No Other Interpretation Can: Final Comparative Table

Irreducible problem	Affected theory	MWI's solution	Why other interpretations fail
Problem of time ($\hat{H}\|\Psi\rangle = 0$ without external time)	LQG / Quantum cosmology	Time emerges from decoherence between branches; Page-Wootters mechanism is a consequence of MWI	Copenhagen needs external classical time; Bohm postulates absolute time; both are circular
Arrow of time without	LQG / Quantum	Irreversible branching by	Other interpretations take

Irreducible problem	Affected theory	MWI's solution	Why other interpretations fail
temporal asymmetry in the laws	thermodynamics	decoherence; entropy = number of accessible branches	the arrow of time as an external assumption
Semiclassical limit: deriving GR from LQG	LQG	Decoherence selects branches with classical geometry satisfying Einstein's equations	Without MWI, selecting the classical geometry requires an additional unfounded principle
Selection principle for the string landscape	M-Theory / Strings	Landscape vacua = Born-weighted branches of the wave function	Copenhagen cannot grant reality to unrealised vacua; Bohm requires superdeterminism
Bulk as emergent in AdS/CFT	M-Theory / Holography	MWI branches on the CFT boundary generate distinct bulk geometries; decoherence crystallises the bulk	Without a superposition of branches, there is no mechanism to generate a superposition of bulk geometries
Ontological derivation of the Born rule	Quantum mechanics / MWI itself	Emerges from the entanglement structure on the holographic boundary	Copenhagen postulates it; Bohm assumes it in initial conditions; both are ad hoc

6. Priority Research Lines

6.1 For the Core of the Thesis

Based on the foregoing analysis, the following research lines are priorities for developing the doctoral thesis in a way that renders the MWI = Multiverse hypothesis technically robust:

- Formalise the Page-Wootters mechanism in the context of LQC (Loop Quantum Cosmology): demonstrate that the semiclassical time that LQC needs to recover classical cosmological dynamics emerges naturally from the entanglement between subsystems within the wave function of the spin network.
- Mapping between the Born measure in MWI and the landscape measure in M-Theory: seek an explicit mapping between the amplitudes of the initial cosmological wave function and the transition probabilities between string landscape vacua. This requires working in the WKB limit of the Hartle-Hawking wave function.
- Explore the ER = EPR conjecture in the MWI context: if entangled pairs of MWI branches are connected by Einstein-Rosen wormholes, this would provide the geometric mechanism by which the bulk emerges from entanglement between branches. This line connects directly with the 'It from Qubit' programme.
- Derive the Born rule from holography in the context of the universal wave function with a CTC: explore whether the self-consistency of the wave function under the CTC imposes the Born rule as the only internally coherent probability distribution.

6.2 Connections with Recent Research

The following recent developments in the literature are especially relevant for the thesis and must be incorporated:

- The work of Aron Wall and collaborators on quantum extremal entropy in AdS/CFT (Engelhardt-Wall formula): provides a precise formulation of how bulk singularities are related to boundary entanglement.
- The 'islands' programme in the black hole information paradox (Penington, Almheiri, Mahajan, Maldacena, Zhao): shows that information is recovered through non-perturbative effects of the wave function, consistent with MWI.
- Jackiw-Teitelboim (JT) gravity as a toy model of AdS2/CFT1: allows exact calculation of the gravitational partition function, which in the MWI interpretation corresponds to the sum over all geometries (all branches).
- The 'geometry from entropy' proposal (Ryu-Takayanagi and its quantum generalisations): minimum-area surfaces in the bulk correspond to entanglement entropy on the boundary, which in MWI corresponds to the 'surface' separating branches.

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7. Conclusions

This report has argued that the Many-Worlds Interpretation can and must be understood as a structural component of a quantum theory of gravity, not as a philosophical interpretation among other equally valid alternatives. Its contributions are asymmetric depending on the theory:

In LQG: MWI resolves the problem of time by providing the internal mechanism — decoherence between branches — by which semiclassical time emerges from a timeless equation (Wheeler-DeWitt). It also provides the mechanism by which the arrow of time emerges without postulating it. No other interpretation can do this without circularity or ad hoc assumptions.

In M-Theory: MWI transforms the landscape problem from a problem of anthropic selection into a problem of quantum amplitudes. Landscape vacua are branches of the universal wave function, and the Born rule provides the probability measure without additional principles. Moreover, through ER = EPR and holography, MWI branches in the boundary theory generate bulk geometries, resolving the problem of how the bulk emerges from quantum entanglement.

The MWI = Cosmological Multiverse hypothesis: in its strong version, states that the universes of the cosmological multiverse (eternal inflation, cyclic models, string landscape) are identical to the branches of the universal wave function. This hypothesis is technically precise, has verifiable consistency conditions, and resolves the universe redundancy that current models cannot address coherently.

The question posed — what MWI contributes to LQG and M-Theory that no other interpretation could — has a concise answer: MWI contributes the emergence mechanism. It is the physical process by which time, classical geometry, probabilities and physical constants emerge from a substrate that is quantum, timeless, lacking classical geometry, lacking probabilities and lacking pre-established constants. Without this mechanism, LQG and M-Theory are incomplete formalisms: they generate the correct structures but cannot explain how those structures become the universe we observe.

> *The final quantum theory of gravity cannot limit itself to unifying LQG or M-Theory with standard quantum mechanics. It must incorporate MWI as the emergence mechanism of the classical world from the quantum-gravitational substrate. The MWI = Cosmological Multiverse hypothesis is the statement that, when this is achieved, it will be discovered that the multiple languages of the multiverse — quantum, inflationary, cyclic, from the landscape — were all descriptions of the same mathematical object: the universal wave function of the universe, evaluated from different perspectives.*

Key References

The following references are fundamental for developing the proposed lines of research:

- Page, D.N. & Wootters, W.K. (1983). Evolution without evolution: Dynamics described by stationary observables. Physical Review D, 27(12), 2885. — Foundation of the time emergence mechanism.
- Maldacena, J. & Susskind, L. (2013). Cool horizons for entangled black holes. Fortschritte der Physik, 61(9), 781-811. — ER = EPR conjecture; bulk emergent from entanglement.
- Van Raamsdonk, M. (2010). Building up spacetime with quantum entanglement. General Relativity and Gravitation, 42(10), 2323-2329. — Spacetime as emergent from entanglement.
- Almheiri, A., Mahajan, R., Maldacena, J. & Zhao, Y. (2020). The Page curve of Hawking radiation from semiclassical geometry. Journal of High Energy Physics. — Islands and information recovery.
- Ryu, S. & Takayanagi, T. (2006). Holographic derivation of entanglement entropy from the anti-de Sitter space/conformal field theory correspondence. Physical Review Letters, 96(18). — Entanglement entropy and geometry.
- Hartle, J.B. & Hawking, S.W. (1983). Wave function of the Universe. Physical Review D, 28(12), 2960. — Boundary conditions of the universal wave function.
- Penington, G. (2020). Entanglement wedge reconstruction and the information paradox. Journal of High Energy Physics. — Entanglement wedges and MWI.
- Everett, H. (1957). Relative state formulation of quantum mechanics. Reviews of Modern Physics, 29(3), 454. — Foundation of MWI.
- Bohm, D. (1952). A suggested interpretation of the quantum theory in terms of hidden variables. Physical Review, 85(2), 166. — Bohmian mechanics as contrast.
- Ashtekar, A. & Singh, P. (2011). Loop quantum cosmology: A status report. Classical and Quantum Gravity, 28(21). — State of the art in LQC.

— End of report —

Working draft for doctoral thesis in Theoretical Physics